Affordable Development and Demonstration of a Small NTR Engine and Stage: A Preliminary NASA, DOE and Industry Assessment
– *Invited Talk* –

EXPL-01 Advanced Propulsion for Exploration

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presented at the

AIAA Space & Astronautics Forum & Exposition (*Space 2014*)
San Diego, CA

Tuesday, August 5, 2014

"Propelling Us to New Worlds"

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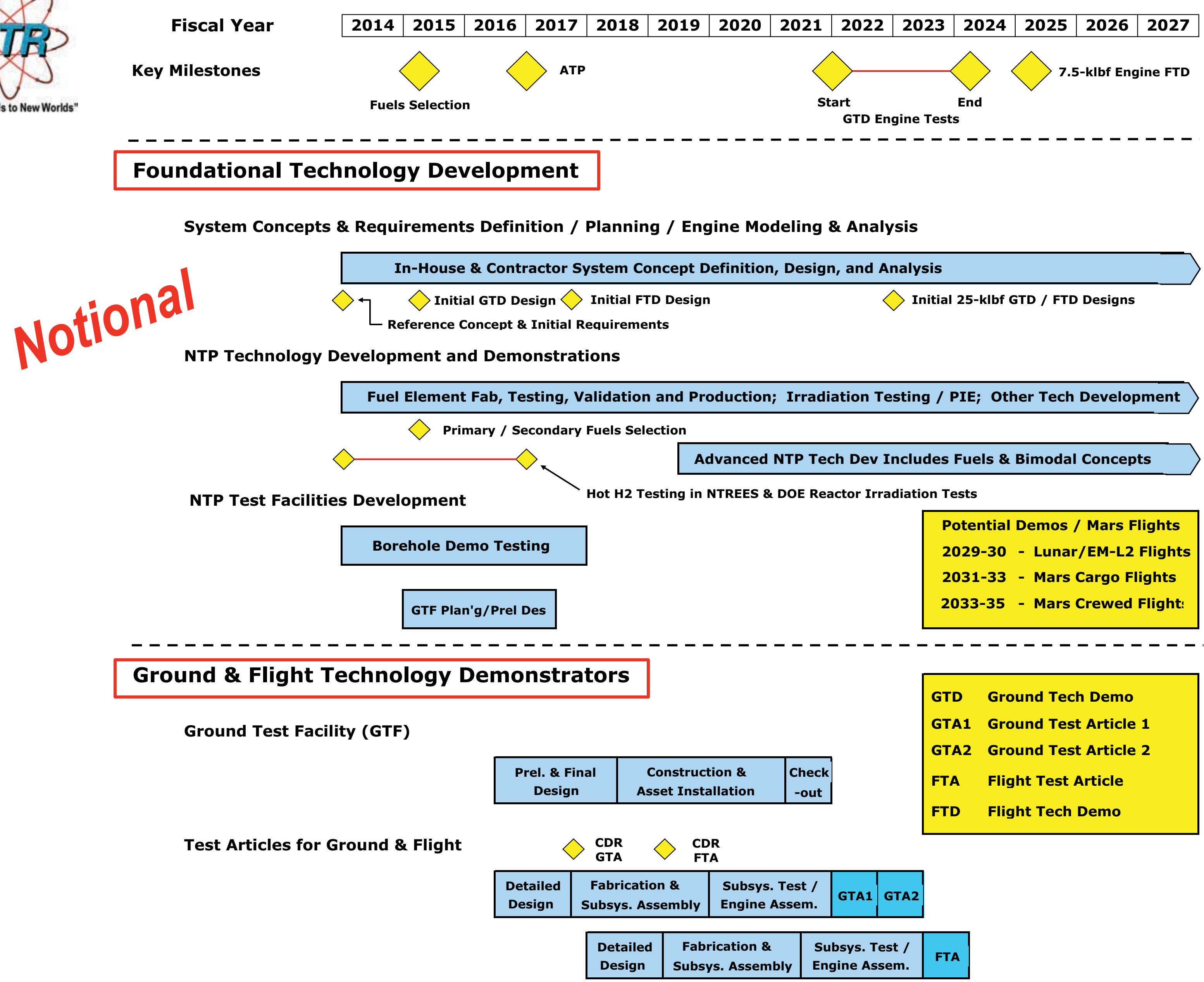
Formulation of Affordable and Sustainable NTP Development Strategy is Underway Involving NASA, DOE and Industry

- In FY' 11, Nuclear Thermal Propulsion (NTP) was identified as a key propulsion option under the Advanced In-Space Propulsion (AISP) component of NASA's Exploration Technology Development and Demonstration (ETDD) program
- A strategy was outlined by GRC and NASA HQ that included 2 key elements – "Foundational Technology Development" followed by specific "Technology Demonstration" projects
- The "Technology Demonstration" element proposed ground technology demonstration (GTD) testing in the early 2020's, followed by a flight technology demonstration (FTD) mission by 2025
- In order to reduce development costs, the demonstration projects would focus on developing a smaller, lower thrust (~7.5 klb_f) engine that utilizes a "common" fuel element design scalable to the higher thrust (~25 klb_f) engines used in NASA's Mars DRA 5.0 study (NASA-SP-2009-566)
- Besides reducing development costs and allowing utilization of existing, flight proven engine hardware (e.g., hydrogen pumps and nozzles), small, lower thrust ground and flight demonstration engines can validate the technology and offer improved capability – increased payloads and decreased transit times – valued for robotic science missions identified in NASA' s Decadal Study
- NASA, DOE (NE-75, ORNL, INL) and industry (Aerojet Rocketdyne) are working together on formulating a strategy leading to the development of a small GTD (~7.5 klb_f) engine in the early 2020' s followed by a FTD "lunar flyby" mission using a small NTP stage (SNTPS) around 2025
- The preliminary assessment provided here along with similar information proposed by DOE/NE-75 provides a strawman for continued refinement allowing an informed cost estimate to be made


Fiscal Year
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
Key Milestones
Fuels Selection
ATP
Start
End
GTD Engine Tests
7.5-klbf Engine FTD
Foundational Technology Development
System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis
In-House & Contractor System Concept Definition, Design, and Analysis
Initial GTD Design
Initial FTD Design
Initial 25-klbf GTD / FTD Designs
Reference Concept & Initial Requirements
NTP Technology Development and Demonstrations
Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development
Primary / Secondary Fuels Selection
Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts
Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests
NTP Test Facilities Development
Borehole Demo Testing
GTF Plan'g/Prel Des
Potential Demos / Mars Flights
2029-30 - Lunar/EM-L2 Flights
2031-33 - Mars Cargo Flights
2033-35 - Mars Crewed Flights
Ground & Flight Technology Demonstrators
Ground Test Facility (GTF)
Prel. & Final Design
Construction & Asset Installation
Check -out
GTD Ground Tech Demo
GTA1 Ground Test Article 1
GTA2 Ground Test Article 2
FTA Flight Test Article
FTD Flight Tech Demo
Test Articles for Ground & Flight
CDR GTA
CDR FTA
Detailed Design
Fabrication & Subsys. Assembly
Subsys. Test / Engine Assem.
GTA1
GTA2
Detailed Design
Fabrication & Subsys. Assembly
Subsys. Test / Engine Assem.
FTA
Notional

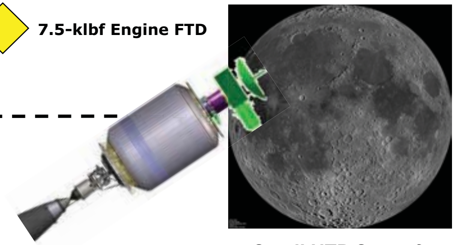
“Propelling Us to New Worlds”

Fiscal Year | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027

Key Milestones

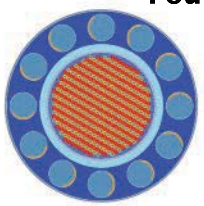
- Fuels Selection
- ATP
- Start / End GTD Engine Tests
- 7.5-klbf Engine FTD

Notional



Small NTP Stage for Lunar Flyby Mission

Foundational Technology Development



SOTA Reactor Core & Engine Modeling

System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis

In-House & Contractor System Concept Definition, Design, and Analysis

- Reference Concept & Initial Requirements
- Initial GTD Design
- Initial FTD Design
- Initial 25-klbf GTD / FTD Designs

NTP Technology Development and Demonstrations

Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development

- Primary / Secondary Fuels Selection
- Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests

Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

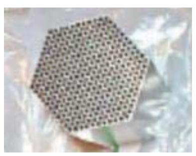
NERVA “Composite” Fuel

Fuel Element Irradiation Testing in ATR at INL

NTP Test Facilities Development

Borehole Demo Testing

GTF Plan'g/Prel Des



“Cermet” Fuel

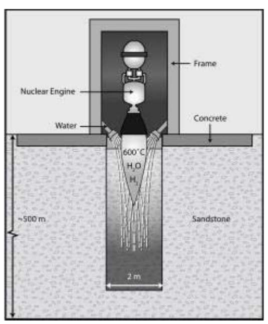
“Fuel-Rich” Engine

Potential Demos / Mars Flights

- 2029-30 - Lunar/EM-L2 Flights
- 2031-33 - Mars Cargo Flights
- 2033-35 - Mars Crewed Flights

Ground & Flight Technology Demonstrators

GTD	Ground Tech Demo
GTA1	Ground Test Article 1
GTA2	Ground Test Article 2
FTA	Flight Test Article
FTD	Flight Tech Demo



Affordable SAFE Ground Testing at the Nevada Test Site (NTS)

Ground Test Facility (GTF)

Prel. & Final Design | Construction & Asset Installation | Check -out

Test Articles for Ground & Flight

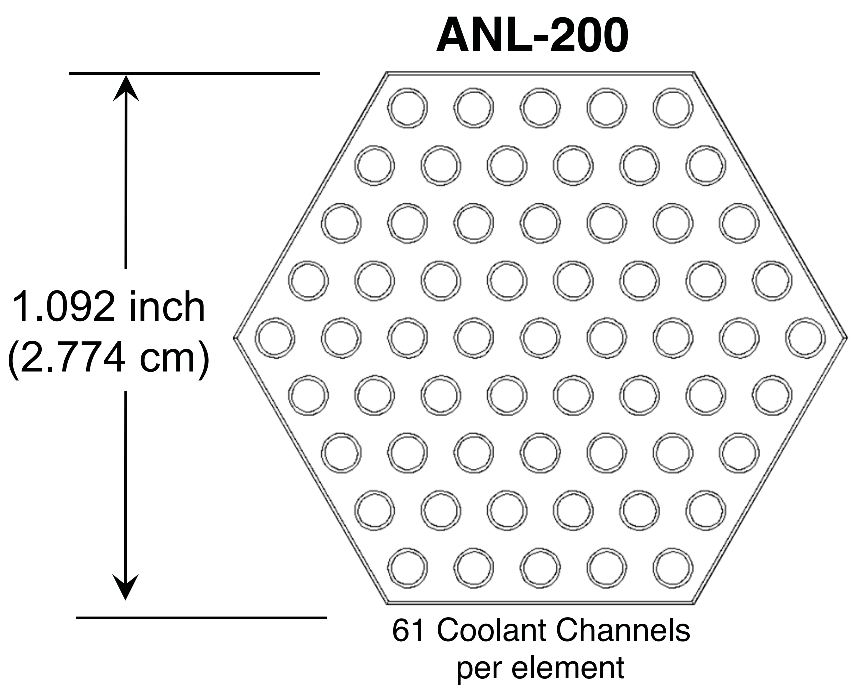
- CDR GTA
- CDR FTA

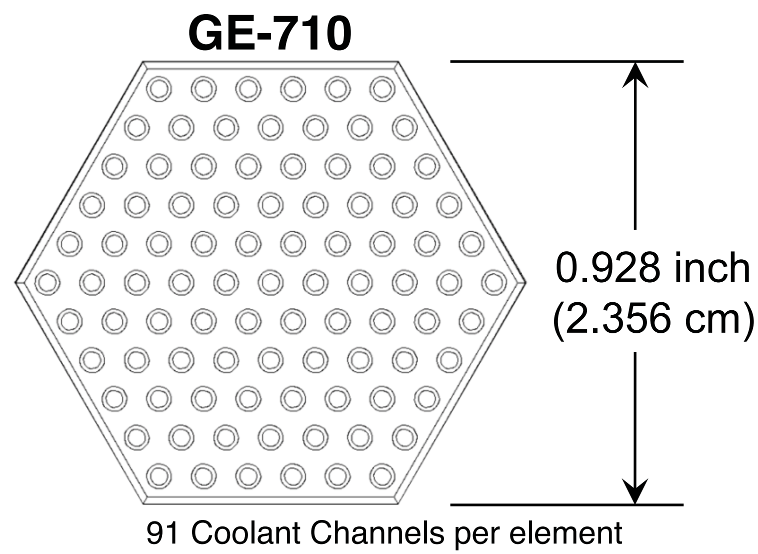
Detailed Design | Fabrication & Subsys. Assembly | Subsys. Test / Engine Assem. | GTA1 | GTA2

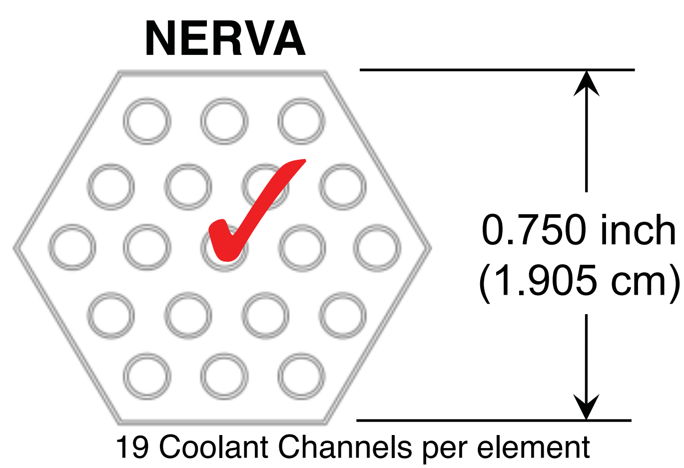
Detailed Design | Fabrication & Subsys. Assembly | Subsys. Test / Engine Assem. | FTA

NTR Element Environmental Simulator (NTREES)

“Heritage” Fuel Element Size Comparisons (Shown to Relative Scale)







S. K. Borowski et al., “Point of Departure” Designs for Small & Full Size (25 klb_f) Composite & Cermet Fuel NTR Engines (March 20, 2013)

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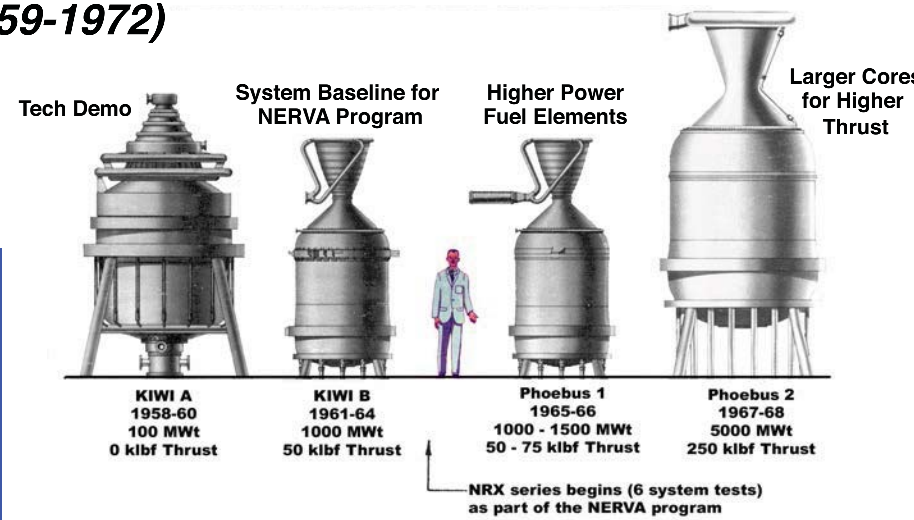
Rover / NERVA* Program Summary

(1959-1972)

The smallest engine tested, the 25 klb$_f$ "Pewee" engine, is sufficient for human Mars missions when used in a clustered arrangement of 3 – 4 engines

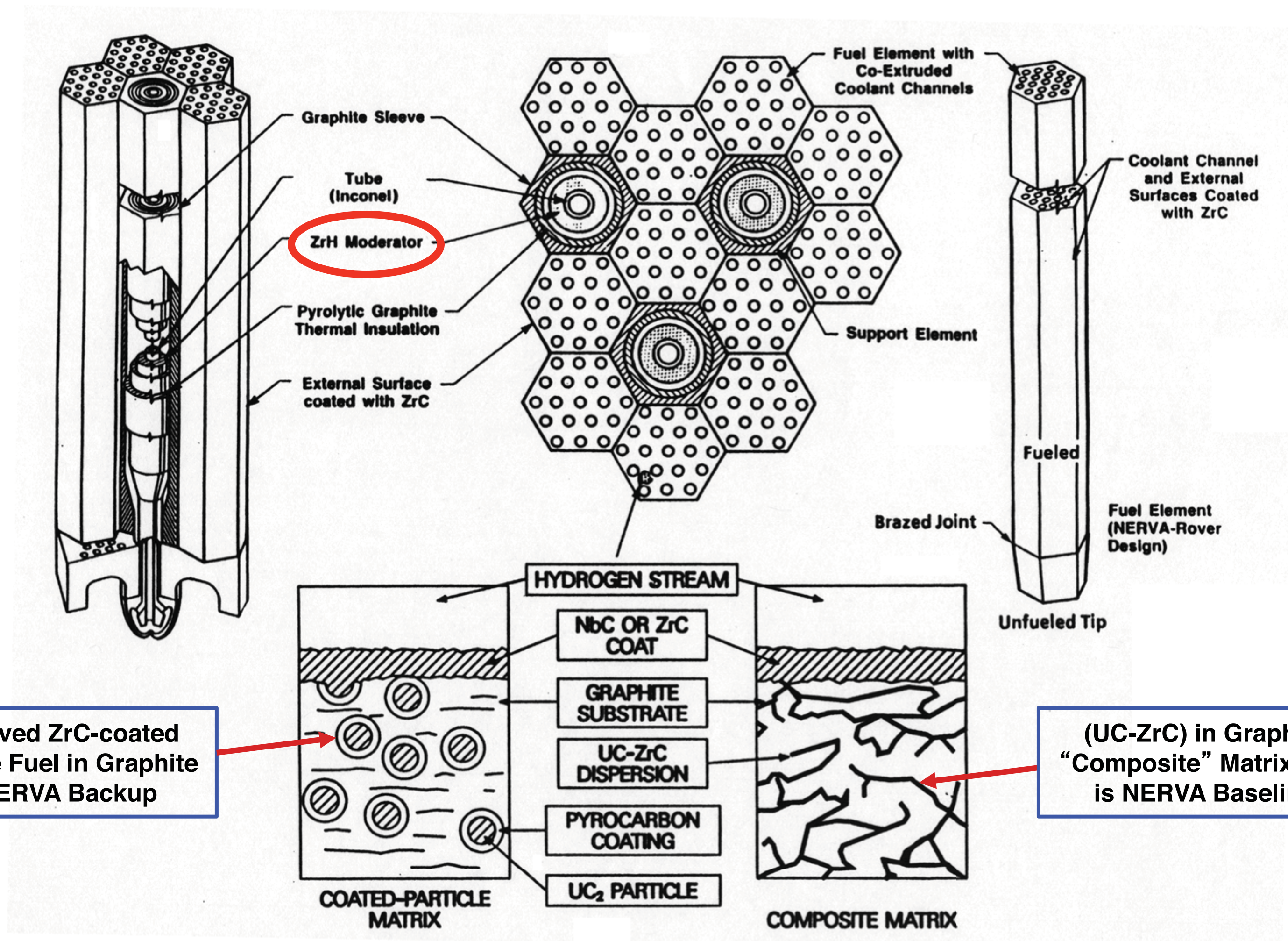
- **20 NTR / reactors designed, built and tested at the Nevada Test Site – "All the requirements for a human mission to Mars were demonstrated"**
- **Engine sizes tested**
  - 25, 50, 75 and 250 klb$_f$
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (in 25 klb$_f$ Pewee)
- **I_{sp} capability**
  - 825-850 sec ("hot bleed cycle" tested on NERVA-XE)
  - 850-875 sec ("expander cycle" chosen for NERVA flight engine)
- **Burn duration**
  - ~ 62 min (50 klb$_f$ NRX-A6 - single burn)
  - ~ 2 hrs (50 klb$_f$ NRX-XE: 27 restarts / accumulated burn time)

**** NERVA: Nuclear Engine for Rocket Vehicle Applications***



The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

"Heritage" Rover / NERVA Reactor Core
Fuel Element and Tie Tube Bundle Arrangement



Improved ZrC-coated Particle Fuel in Graphite is NERVA Backup

(UC-ZrC) in Graphite "Composite" Matrix Fuel is NERVA Baseline

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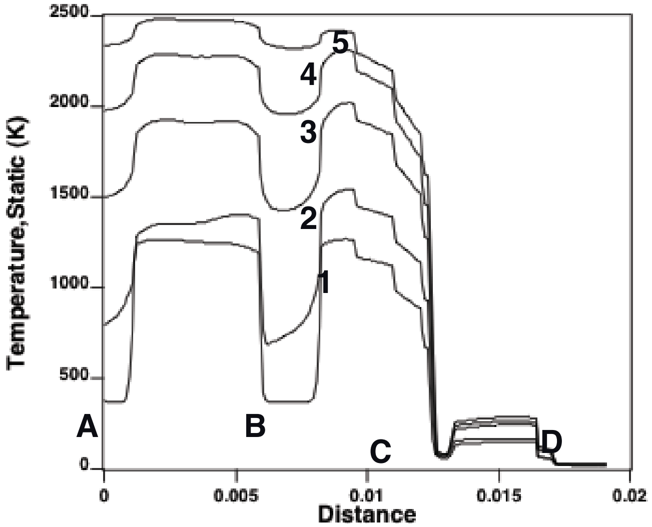
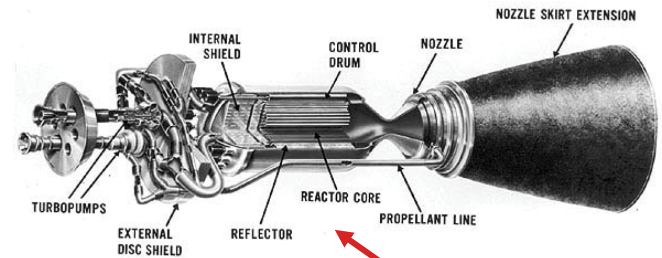
Idaho National Laboratory

GRC / INL Integrated Neutronics, Multi-Physics & Engine Modeling Approach

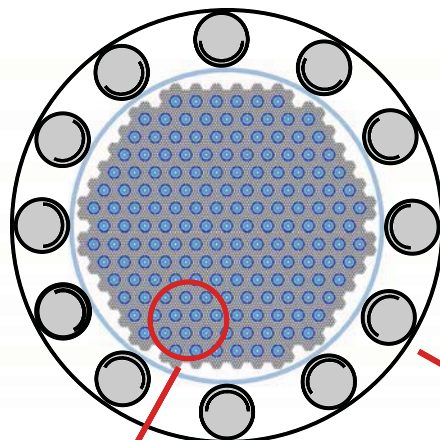
Temperature Distribution Across FE and TT



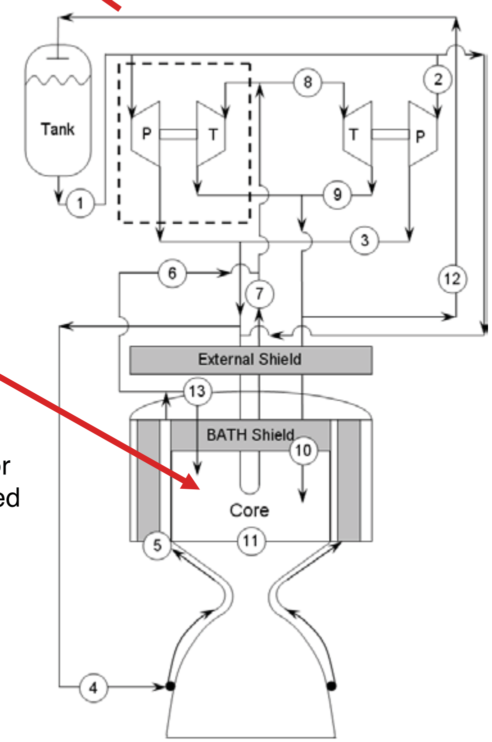
Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)



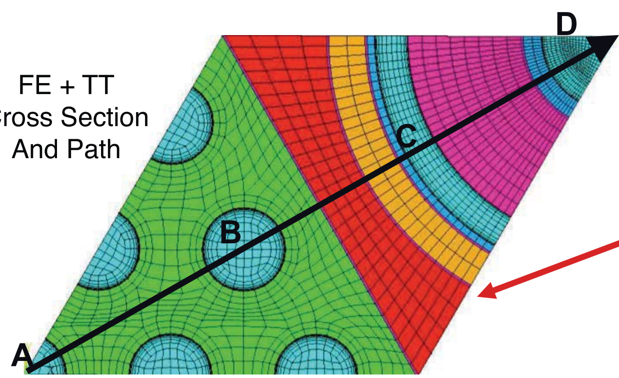
Performance, Size & Mass estimation



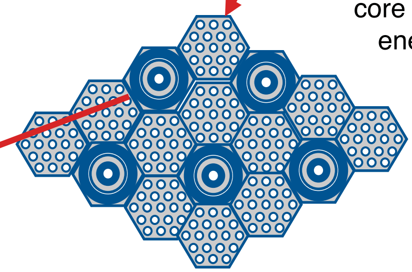
MCNP neutronics for core criticality, detailed energy deposition, and control worth



FE + TT Cross Section And Path



ANSYS Model

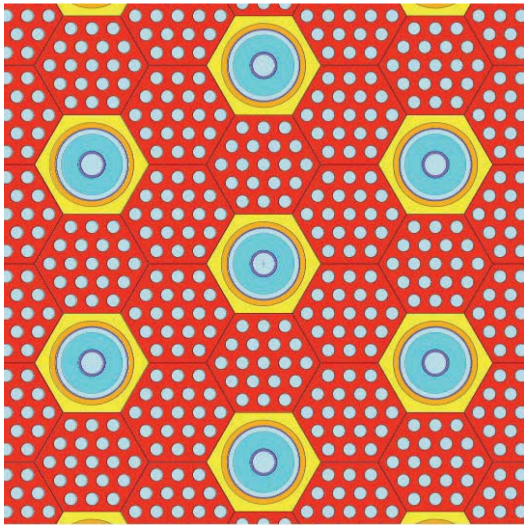


Fuel Element-to-Tie Tube ratio varies with engine thrust level

Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data

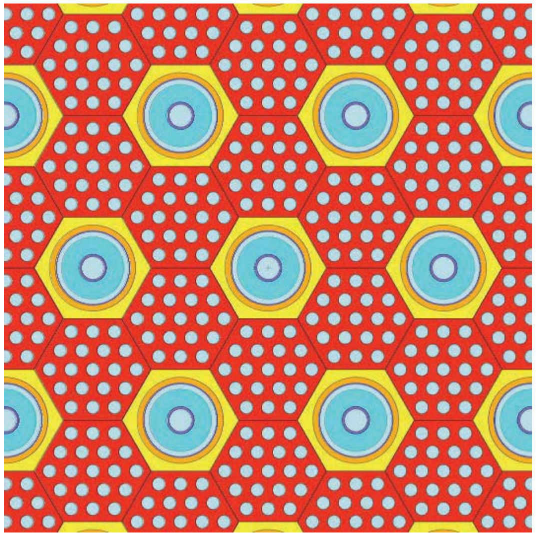
Fuel Element (FE) – Tie Tube (TT) Arrangements for NERVA-derived NTR Engines

"Sparse" FE – TT Pattern used for Large Engines



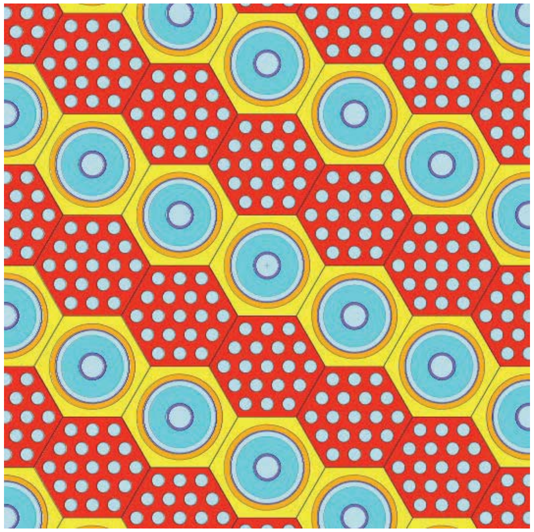
Each FE has 4 adjacent FEs and 2 adjacent TTs with a FE to TT ratio of ~3 to 1

"SNRE" FE – TT Pattern used in Small Nuclear Rocket Engine



Each FE has 3 adjacent FEs and 3 adjacent TTs with a FE to TT ratio of ~2 to 1

"Dense" FE – Tie Tube Pattern used in Lower Thrust Engines



Each FE has 2 adjacent FEs and 4 adjacent TTs with a FE to TT ratio of ~1 to 1

NOTE: An important feature common to both the Sparse and SNRE FE – TT patterns is that each tie tube is surrounded by and provides mechanical support for 6 fuel elements

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

Development of Common Scalable Fuel Elements for Development & Testing

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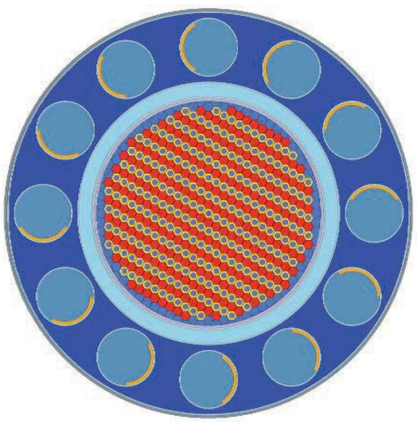
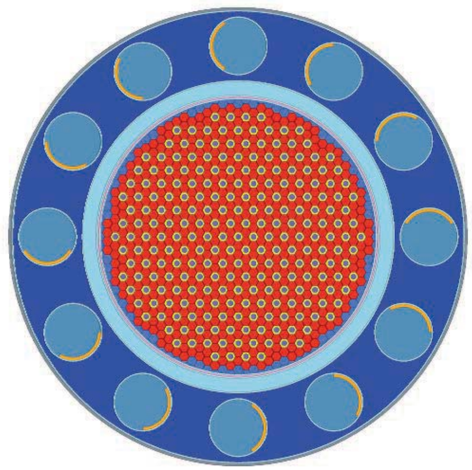
- During the Rover program, a common fuel element / tie tube design was developed and used in the design of the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968)

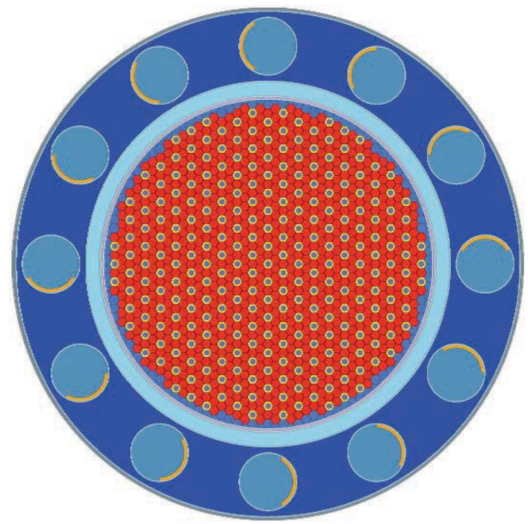
- NASA and DOE are evaluating a similar approach: design, build, ground then flight test a small engine using a common fuel element that is scalable to a larger 25 klbf thrust engine needed for human missions



7.4-klb$_f$ low thrust engine



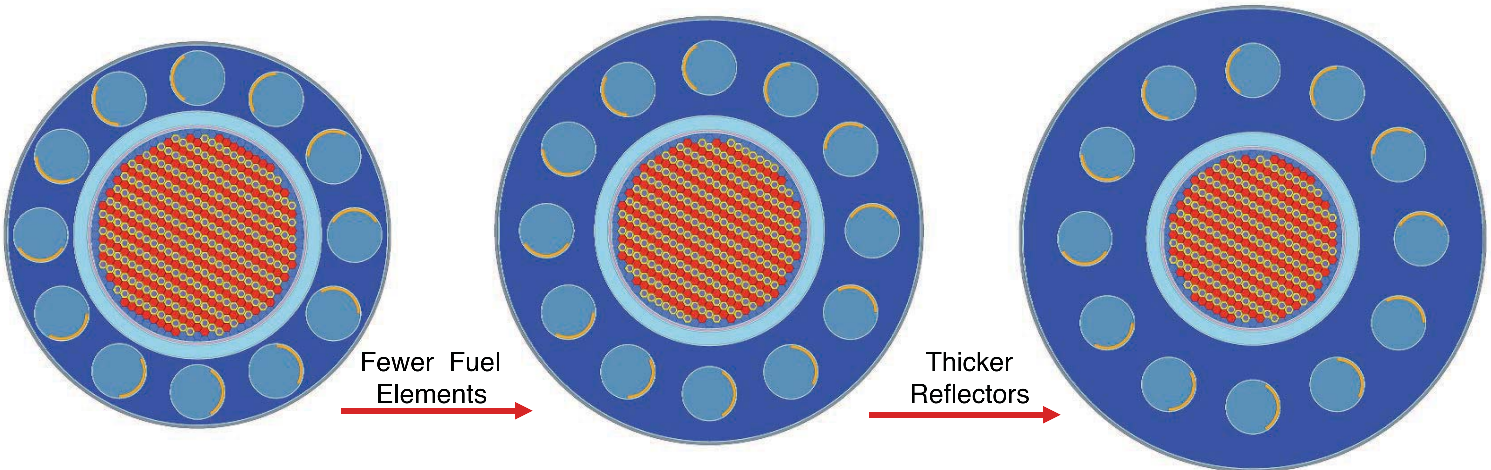
16.4-klb$_f$ SNRE



25-klb$_f$ "Pewee-class" engine
(Radial growth option / sparse pattern)

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846 paper presented at the 47th Joint Propulsion Conference, San Diego, CA

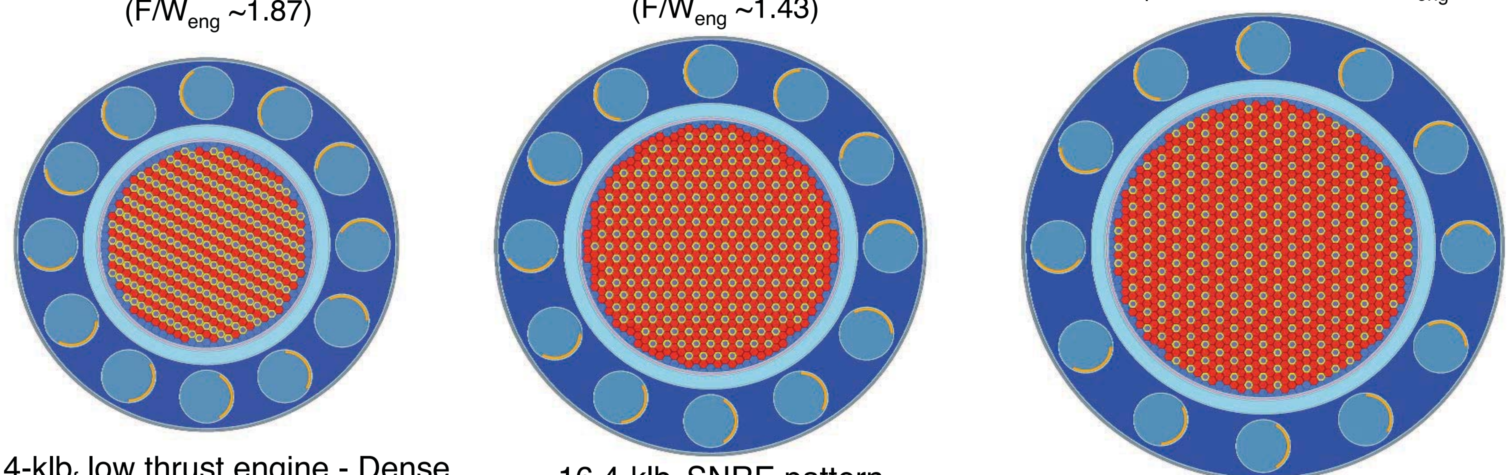
Cross Sections for Low to High Thrust Engines using Various Fuel Element – Tie Tube Patterns



7.4-klb$_f$ thrust engine (F/W$_{eng}$ ~1.87)

6.0-klb$_f$ thrust engine (F/W$_{eng}$ ~1.43)

5.3-klb$_f$ thrust engine (F/W$_{eng}$ ~1.10)



7.4-klb$_f$ low thrust engine - Dense

16.4-klb$_f$ SNRE pattern

25-klb$_f$ “Pewee-class” engine (Radial growth / Sparse pattern)

Ref: B. Schnitzler, et al., “Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design”, AIAA-2011-5846

(Same Scale for all Concepts)

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Oak Ridge National Laboratory

Idaho National Laboratory

Performance Characteristics for Small & Full Size NERVA-derived Engine Designs – Composite Fuel

Performance Characteristic	7,420-lbf Option	SNRE Baseline	Axial Growth Option Nominal	Axial Growth Option Enhanced	Radial Growth Option Nominal	Radial Growth Option Enhanced
	★		★		?	
Engine System						
Thrust (klb_f)	7.42	16.4	25.1	25.1	25.1	25.1
Chamber Inlet Temperature (K)	2736	2695	2790	2940	2731	2807
Chamber Pressure (psia)	1000	450	1000	1000	1000	1000
Nozzle Expansion Ratio (NAR)	300:1	100:1	300:1	300:1	300:1	300:1
Specific Impulse (s)	894	875	906	941	894	913
Engine Thrust-to-Weight	1.87	2.92	3.50	3.50	3.60	3.60
Reactor						
Active Fuel Length (cm)	89.0	89.0	132.0	132.0	89.0	89.0
Effective Core Radius (cm)	14.7	29.5	29.5	29.5	35.2	35.2
Engine Radius (cm)	43.9	49.3	49.3	49.3	55.0	55.0
Element Fuel/Tie Tube Pattern Type	Dense	SNRE	SNRE	SNRE	Sparse	Sparse
Number of Fuel Elements	260	564	564	564	864	864
Number of Tie Tube Elements	251	241	241	241	283	283
Fuel Fissile Loading (g U per cm^3)	0.60	0.60	0.25	0.25	0.45	0.45
Maximum Enrichment (wt% U-235)	93	93	93	93	93	93
Maximum Fuel Temperature (K)	2860	2860	2860	3010	2860	2930
Margin to Fuel Melt (K)	40	40	190	40	110	40
U-235 Mass (kg)	27.5	59.6	36.8	36.8	68.5	68.5

NOTE: Fuel Matrix Power Density: 3.437 MW_t / liter

SOTA "Pewee-class" Engine Parameters

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

NTP Fuels and Engine Development Sequence
Nuclear & Non-Nuclear Testing

Fuel Specimens

- Fabrication and characterization
- High temperature testing including hot H_2 exposure and flow rates
- Irradiation testing at high temperature

Fuel Elements (Prototypic Cross-Section, Segments or Full Length)

- Fabrication and characterization
- High temperature testing including H_2 exposure and prototypic flow rates (e.g., NTREES)
- Irradiation testing

Reactor Design

- Neutronics and Physics
- Heat Transfer
- Dynamics
- Structures
- I&C

Engine Ground Test

- Prototypic fuel temperatures, hot H_2 flow rates, and operating times
- Engine test also serves as fuel qualification test

Addressing Ground Test Challenges

- Utilize the SAFE borehole concept
- Use temporary facilities & services at the ground test site
- Minimize engine size & number of tests to qualify for launch
- Maximize existing facilities (e.g., DAF) and capabilities for testing and PIE

Ref: J. Werner, 47th AIAA JPC, INL, 2011

NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project

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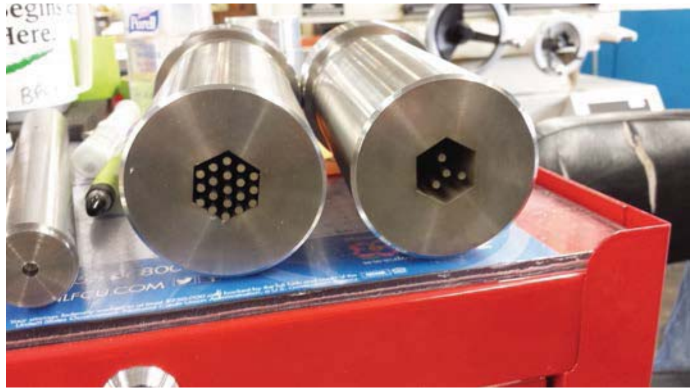
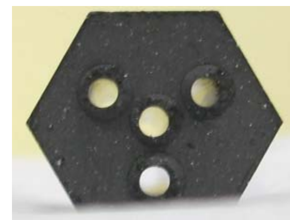
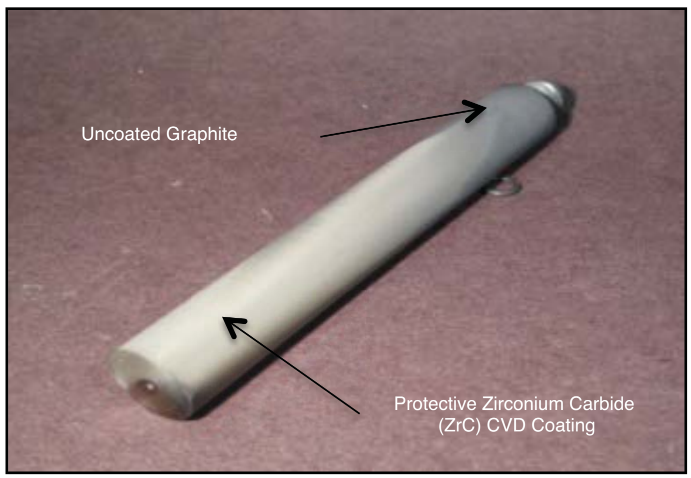


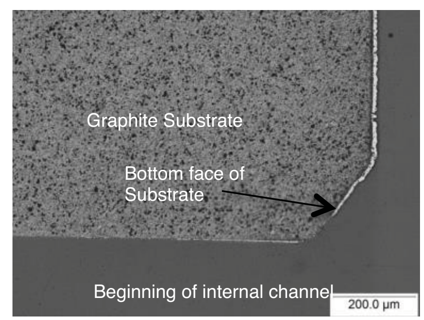
Above: 19 and 4-hole NERVA fuel element extrusion extrusion dies; Left: Graphite extruder with vent lines installed for DU capability



Above and Left: Extrusion samples using carbon-matrix/Ha blend 0.75” across flats, 0.125” coolant channels



Above: Test Piece highlighting ZrC Coating
Right: Coating primarily on external surface

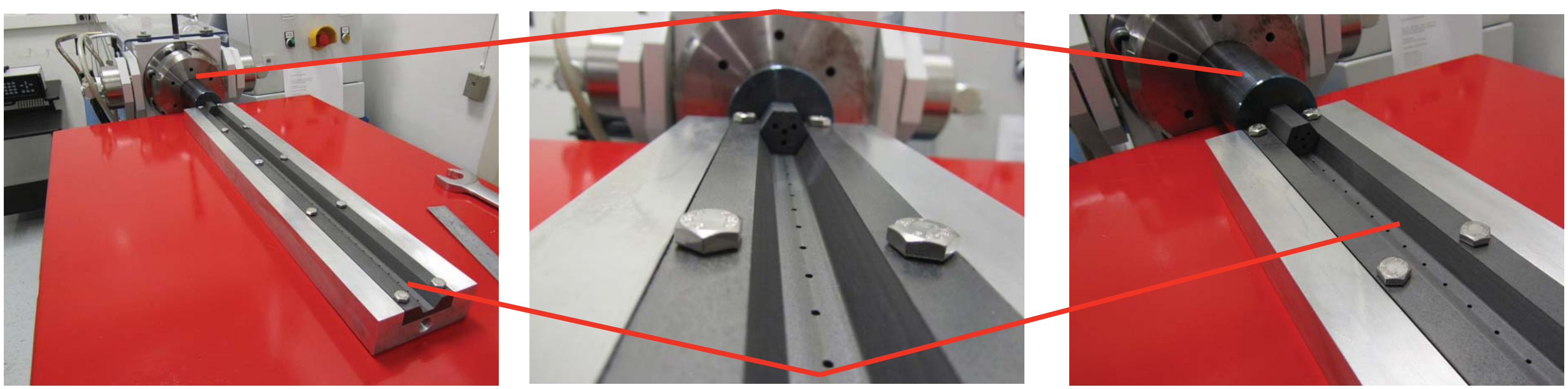


Right: Layoff base / Graphite insert

NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project

- Fuel Fabrication
  - Layoff base/graphite insert has been fabricated and installed.
  - New feed materials (graphite, resin, and ZrC) have been ordered.
  - A new 19-hole extrusion die has been designed and fabricated.
  - Modifications have been made to the 4-hole hexagonal die design to reduce friction during extrusion.
  - 4-hole fuel elements will be used first to establish ZrC coating specs, then will transition to prototypic NERVA-type 19-hole element.
  - Elements with depleted uranium (DU) will undergo rf-heating tests first before enriched uranium elements are tested in DOE reactor.

Extruder



Layoff Table

Maximize Use of NTS, DAF and Existing Bore Holes for Testing

- Testing should be conducted at the Nevada Test Site (NTS) using SAFE (Subsurface Active Filtration of Exhaust) approach in existing Boreholes.

- NTS provides a large secure, safety zone for conducting NTR testing.

- The Device Assembly Facility (DAF) is located within the NTS and is available for pre-test staging (assembly & "0-power" critical testing) of engine's reactor system prior to transfer to borehole test location also within the NTS.

- DAF is a collection of more than 30 individual steel-reinforced concrete test cells connected by a large rectangular common corridor. Entire complex is covered by compacted earth and spans an area of ~100,000 ft^2.

- DAF has multiple assembly / test cells; also high bays with multi-ton crane capability. The assembly cells designed to handle weapons grade materials; *cells rated for handling up to ~60 kg of enriched U-235 which is twice the amount found in the small 7.42 klb_f NTRE.*

Aerial View of the DAF at the Nevada Test Site

Non-Nuclear Subscale SAFE Bore Hole Feasibility Test

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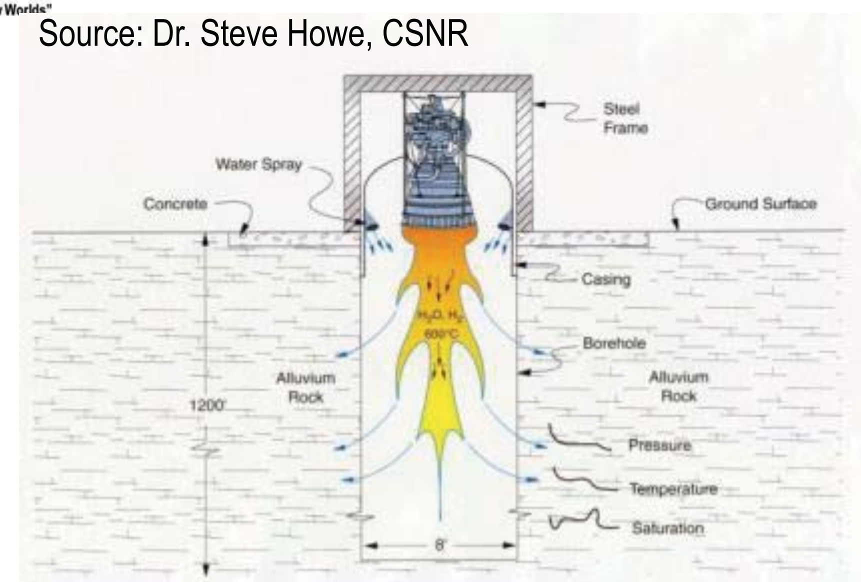
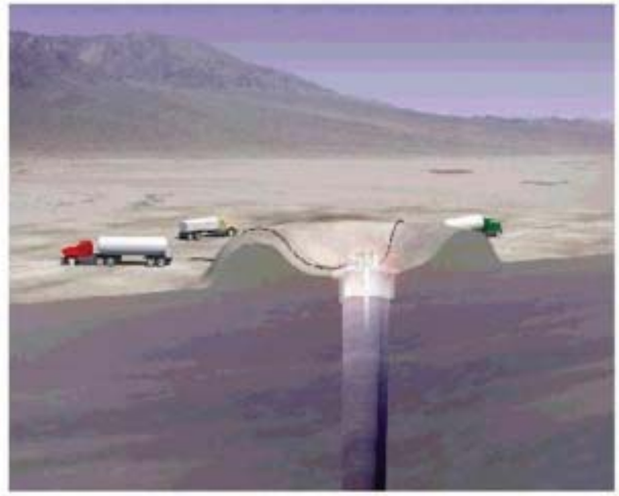
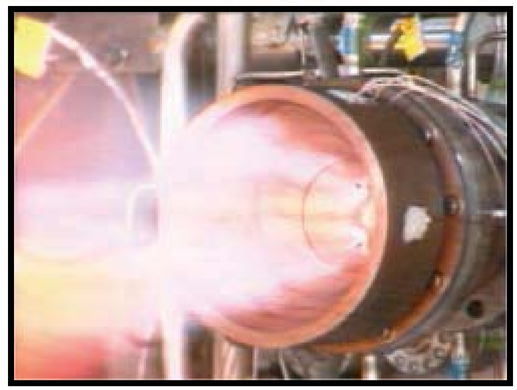


Schematic at left shows the idealized configuration of the testing concept including the mounting pad, containment, water spray, and dispersion profiles

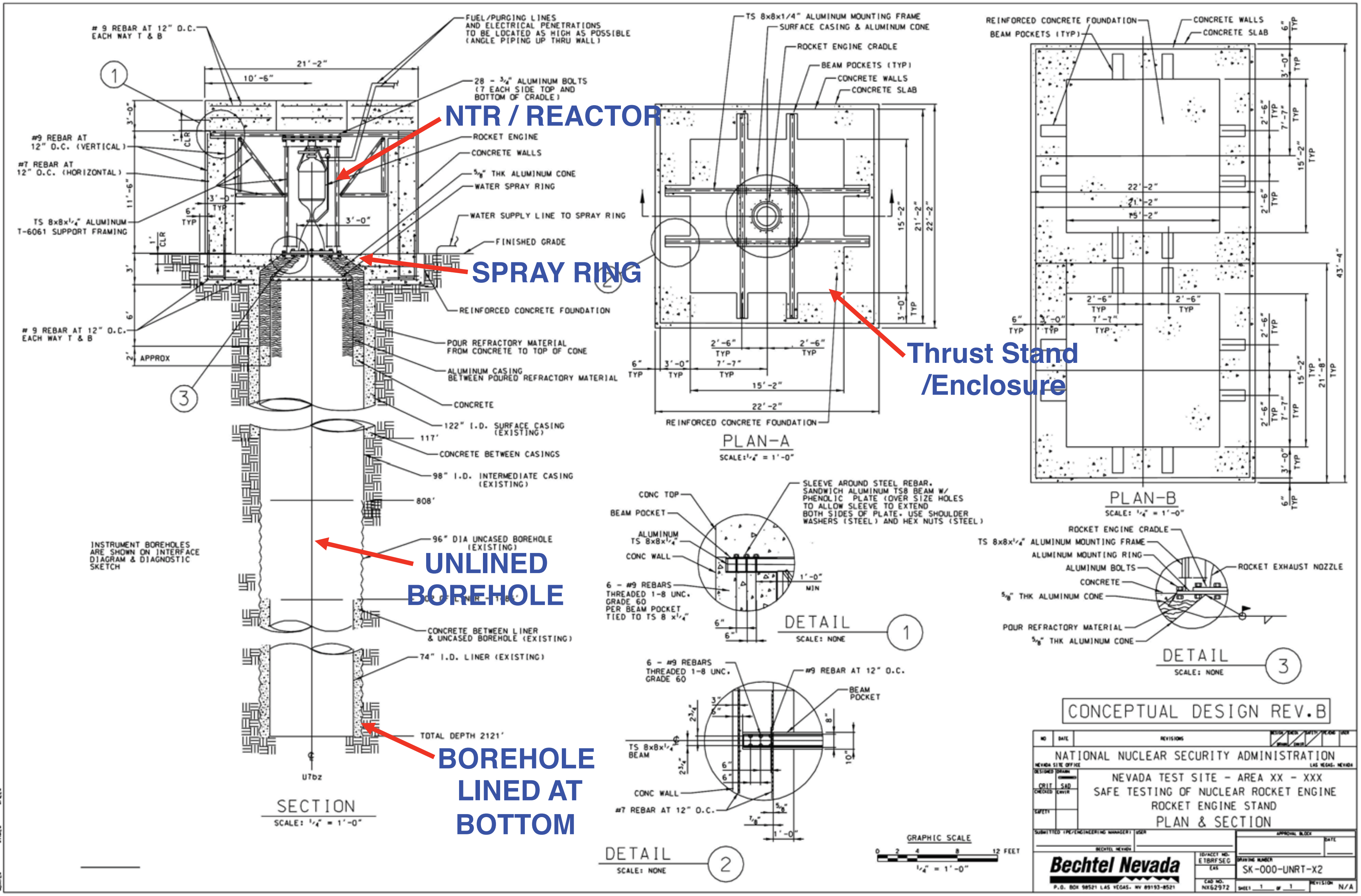


- Driving the hydrogen exhaust into the alluvium soil at the NTS allows capture of gases in a geology proven to contain heavy elements
- Fission products (if any) exhausted into the hole will be trapped into the soil strata at low concentrations ~10^{-9} gms/cm^3
- Use of the bore hole as an "in-situ" exhaust scrubber system potentially offers a low cost testing option for NTR
- Potential option is to have a suitably sized subscale validation test performed in the Phase II NCPS effort for ~$2M
- Component inventory and cost breakdown for subscale test being reevaluated by GRC and DOE to identify potential savings

SAFE: Subsurface Active Filtration of Exhaust



Aerojet-Rocketdyne's ~2.1-klbf "fuel rich" H/O engine is an attractive option for non-nuclear, subscale validation testing



NTR / REACTOR
SPRAY RING
Thrust Stand /Enclosure
UNLINED BOREHOLE
BOREHOLE LINED AT BOTTOM
CONCEPTUAL DESIGN REV.B
NATIONAL NUCLEAR SECURITY ADMINISTRATION
NEVADA TEST SITE - AREA XX - XXX
SAFE TESTING OF NUCLEAR ROCKET ENGINE
ROCKET ENGINE STAND
PLAN & SECTION
Bechtel Nevada
SK-000-UNRT-X2
SECTION
PLAN-A
PLAN-B
DETAIL 1
DETAIL 2
DETAIL 3
TOTAL DEPTH 2121'

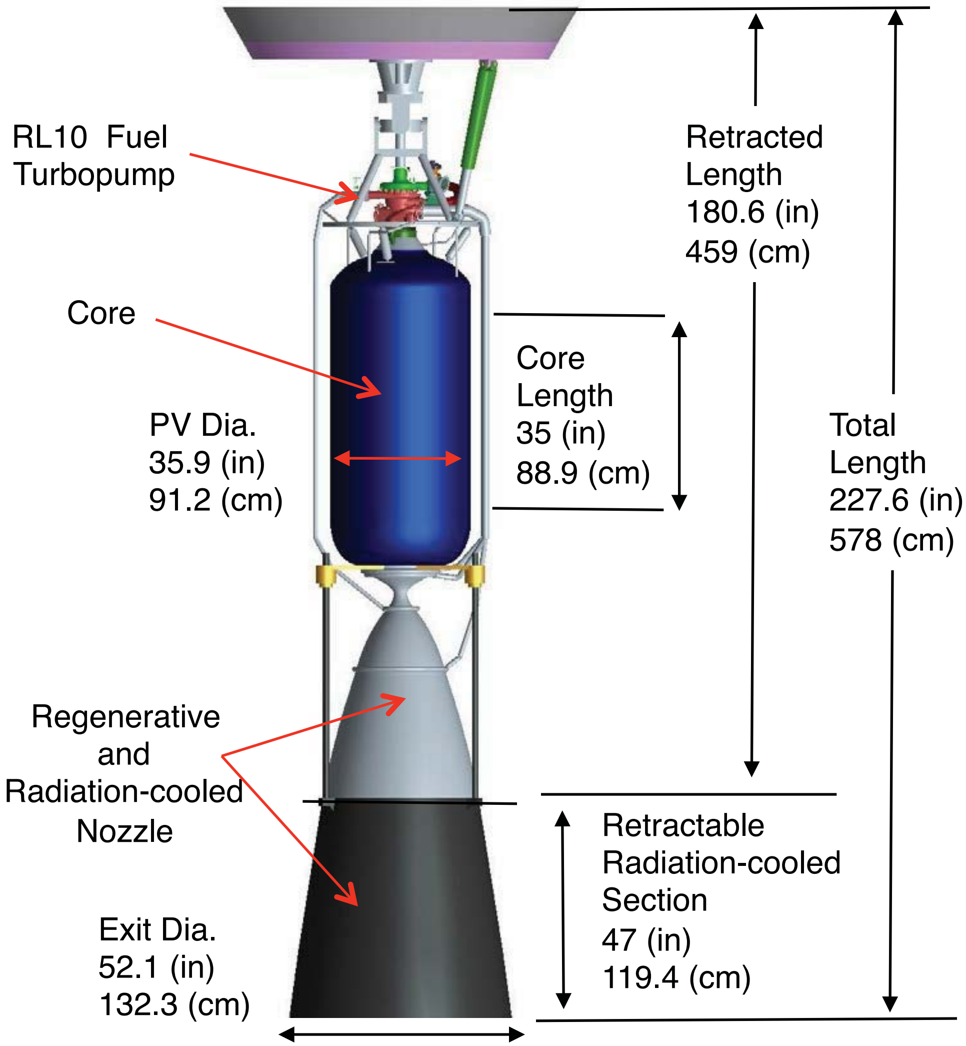
Trailers Configured for Controls and Measurements Readily Moved to Other Test Areas

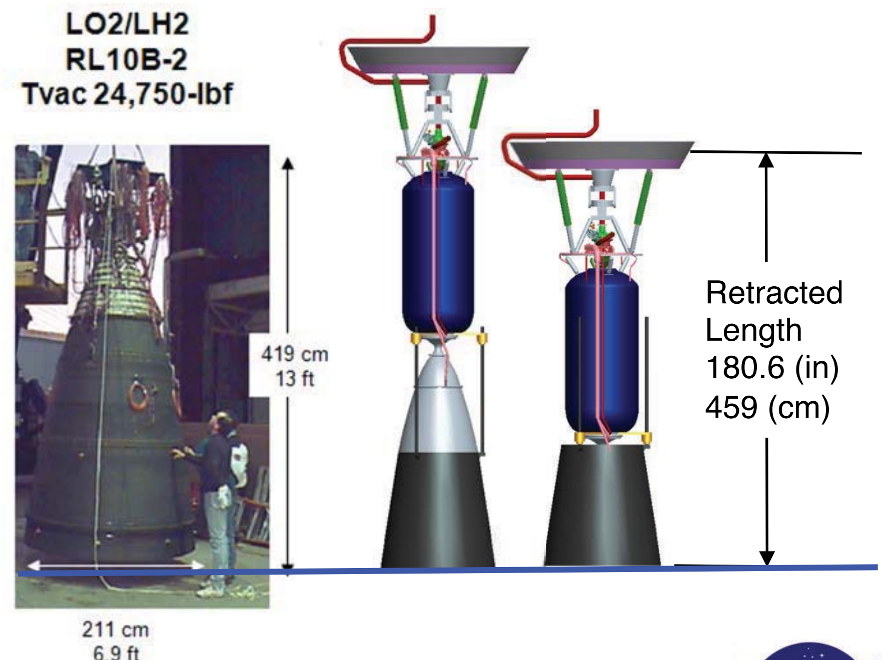
Other Nuclear Tests

- Cold Critical Experiments
  - Confirmation of critical configuration
  - Excess Reactivity
  - Static physics/safety parameters
- Hot Critical Experiments
  - Kinetics parameters
  - Safety coefficients (feedback)
- Gamma/Neutron Exposures
  - Irradiations to establish tolerance

Small NERVA-derived 7.42 klb$_f$ NTR Engine Layout and Dimensions

Aerojet Rocketdyne has been working with GRC to define a small, low thrust NTR scalable to higher thrust engines





Current Liquid Rocket and Stage Technologies are Leveraged to Create Affordable NTP Approach

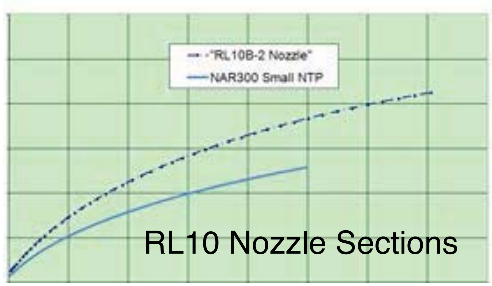
"Propelling Us to New Worlds"

Aerojet Rocketdyne specific chemical liquid rocket engine hardware can be leveraged to reduce the time and cost to develop the small NTP Stage

- The small NTP engine turbo pumps, valves, and nozzles manufactured from same production lines as RL10 and J-2X
  - Small NTP uses RL10 fuel turbopump and nozzle is smaller than current RL10B-2 on Delta 4; could use LOX TP with gas supply to get to Lox-Augmentation of hot hydrogen exhaust
- NTP Stage uses hydrogen tank, avionics, valves from Delta 4 cryogenic stage

RL10 Hydrogen Turbo pump

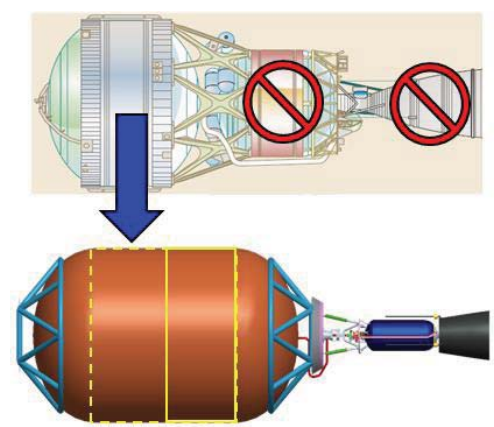
J-2X Chamber Design



RL10 Nozzle Sections

Same Barrel & Dome Sections

Same Diameter Tank Design



Source: Russ Joyner, Aerojet Rocketdyne, GRC-funded work 2011

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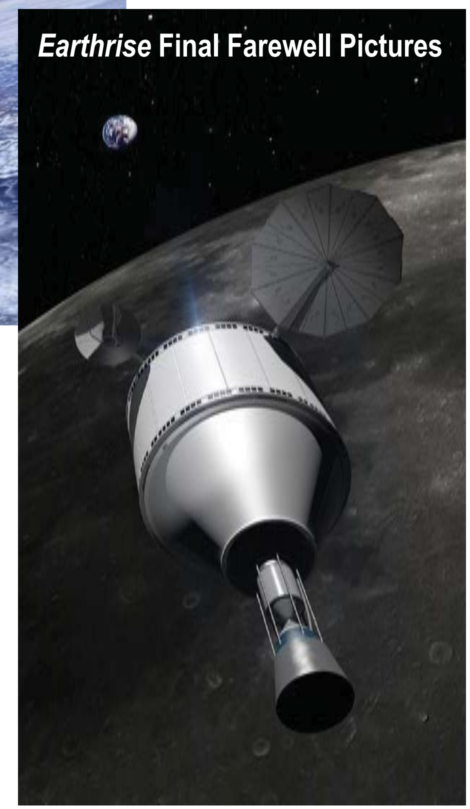
2025 Small NTPS FTD Mission: “Single-Burn Lunar Flyby”

- ELV launches Small NTPS (SNTPS) to LEO (407 km)
- 3 – Day LEO to Moon Transit
- Lunar Gravity Assist and disposal

SNTPS FTD Launch on Delta 4 M (5,4)


DCSS delivers SNTPS to LEO


Earthrise Final Farewell Pictures


Single-Burn TLI sends SNTPS to the Moon


Lunar Gravity Assist sends SNTPS into Deep Space

- IMLEO ~12.72 t
- F ~7.42 klb$_f$, I_{sp} ~900s, F/W$_{eng}$ ~1.87
- LH_2 mass ~5.07 t
- Stage dry mass ~7.40 t
- PL ~250 kg
- Burn time ~20.9 mins

Assumptions for "Sporty" SNTPS GTD & FTD Mission Schedule

- A 10-year period to a ground tested "qualification engine" by 2024 is conceivable but challenging and many things must line up / flow well.

- By necessity it would be a success-oriented high–risk activity requiring immediate and serious financial commitments to the following areas:
  - Management and acquisition approach is streamlined
  - Composite fuel is the baseline and fuel element (FE) production levels are scaled up prior to complete verification of all processing activities; Testing conducted in bore holes at NTS
  - NEPA and launch safety analyses is initiated along with ID'ed shipping and ATLO facility mods

- A single co-located nuclear "skunk works" type temporary facility is sited at the NTS near the site of the candidate bore holes. Its function would be reactor assembly, criticality testing, and subsequent disassembly. Required equipment would be procured as "turn-key" for placement in the building. A single hot cell module (similar to that used by the UK at their Sellafield hot cell facility) would be used to disassemble and inspect the reactors after operation. After disassembly, small groupings of parts would be shipped off-site for final disposal in existing shipping casks.

- The GTD program would focus on borehole testing of three units:
  1) prototype reactor and engine (80% fidelity) in 2022
  2) engineering reactor and engine (90% fidelity) in 2023
  3) qualification engine (100% fidelity) in 2024 after qual-level testing (e.g., vibration) in 2023;
  The flight unit – identical to the qualification unit – would be launched in 2025

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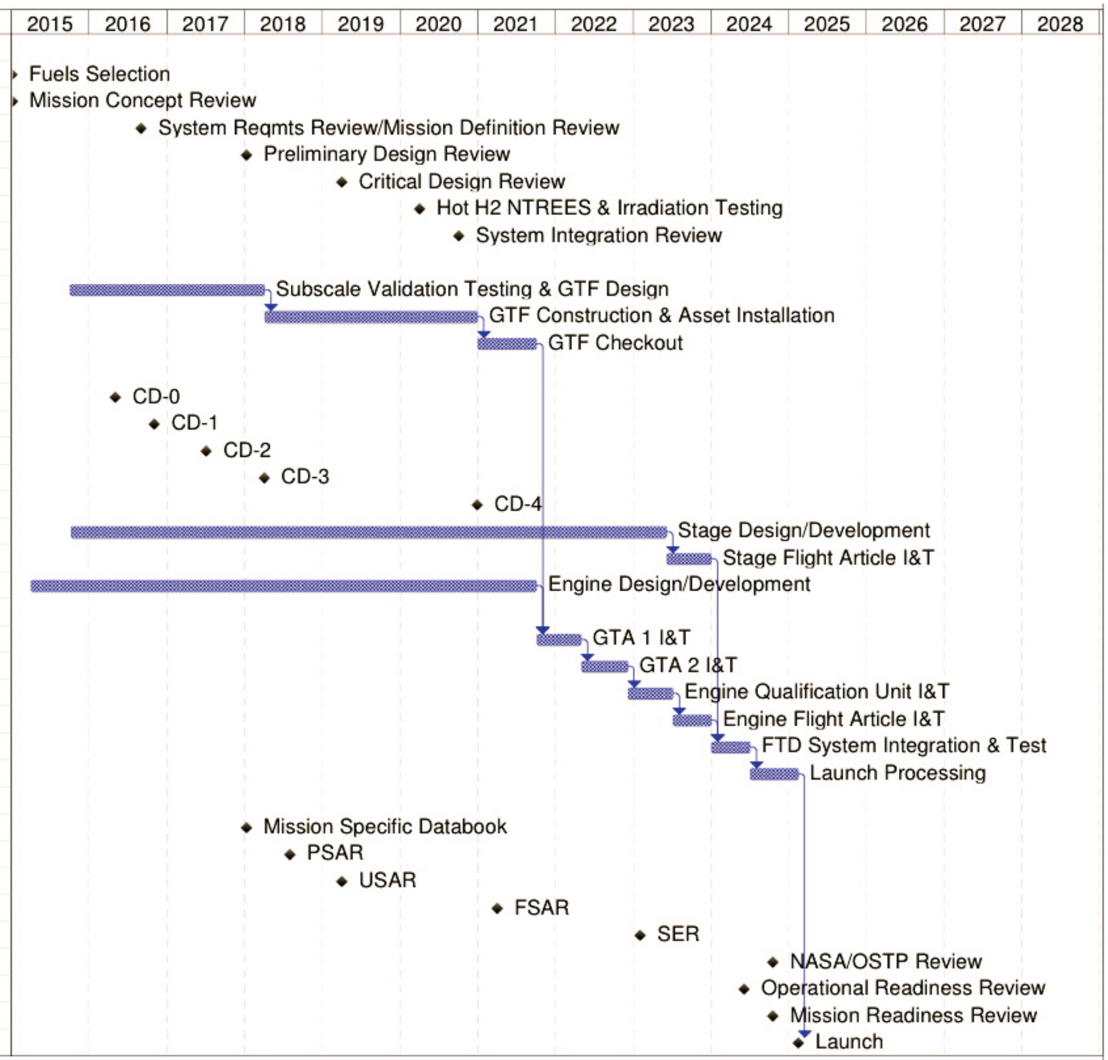
Notional NTP Ground & Flight Test Demonstration Milestone Schedule

ID	Task Name
1	NTP Flight Technology Demonstrator (FTD)
2	Fuels Selection
3	Mission Concept Review
4	System Reqmts Review/Mission Definition Review
5	Preliminary Design Review
6	Critical Design Review
7	Hot H2 NTREES & Irradiation Testing
8	System Integration Review
9	Borehole Test Facility
10	Subscale Validation Testing & GTF Design
11	GTF Construction & Asset Installation
12	GTF Checkout
13	Test Facility Critical Decision Reviews
14	CD-0 : Planning
15	CD-1 : Preliminary Design
16	CD-2 : Final Design
17	CD-3 : Construction
18	CD-4 : Checkout
19	Stage Design/Development
20	Stage Flight Article I&T
21	Engine Design/Development
22	Engine Integration & Test
23	GTA 1 I&T
24	GTA 2 I&T
25	Engine Qualification Unit I&T
26	Engine Flight Article I&T
27	FTD System Integration & Test
28	Launch Processing
29	Launch Approval
30	Mission Specific Databook
31	PSAR
32	USAR
33	FSAR
34	SER
35	NASA/OSTP Review
36	Operational Readiness Review
37	Mission Readiness Review
38	Launch



Not Quite So Sporty Schedule

"Propelling Us to New Worlds"

Control System Test Facilities
Component Safety Test Facilities
Training and Simulator Test Facilities

fuel development and testing
fuel and material Irradiation test facilities at existing reactor
HEU fuel fabrication facility in existing CAT 1 facility
fuel qualification

ground test facility assuming borehole testing w/o effluent system
reactor assembly facility
Remote Inspection/Post-Irradiation Examination Facilities
fuel element and bundle separate effects testing for qualification
reactor design
shield design and fabrication
stage integration

ground test unit
ground test
ground test unit
ground test
qualification unit
Flight unit

transportation assuming one new shipping cask

CAT 1 Flight Assembly and ATLO facility

Reviews and Approvals from NEPA and facility ORRs through INSRP

launch

Summary and Conclusions

- NASA, DOE (NE-75, ORNL, INL) and industry (Aerojet Rocketdyne) are working together on formulating a strategy leading to the development of a small GTD (~7.5 klb_f) engine in the early 2020's followed by a FTD mission using a small NTP stage (SNTPS) around 2025

- 10-years to a ground tested "qualification engine" by 2024 will require immediate, serious financial commitment along with a streamlined management and acquisition approach – *DOE*

- Graphite-based "composite fuel" is the baseline; an engine using this fuel type can be built sooner than one using another less established / less tested fuel at relevant conditions – *DOE*

- Testing should be conducted at the NTS using existing bore holes and/or tunnels; should maximize the use of existing facilities and consider temporary new facilities as required; new nuclear infra-structure is a long lead item – *DOE*

- If graphite-based fuel and borehole testing are not used, years of additional schedule and significant additional dollars will be required – *DOE*

- The FTD mission proposed by GRC is a single-burn "lunar flyby" mission to keep it simple and more affordable; small size engine and stage can also reduce development costs & allowing utilization of existing, flight proven engine hardware (e.g., hydrogen pumps and nozzles) – *Aerojet Rocketdyne*

If you want to go somewhere soon you need to get moving now - DOE